BASEBAND PREDISTORTION METHOD FOR MULTICARRIER TRANSMITTERS

FIELD OF THE INVENTION

This invention relates to transmitting and amplifying signals that at the baseband are digital and more specifically to applying a predistortion algorithm to compensate for inaccuracies introduced by amplifiers, filters and modulator in a multicarrier transmitter. The biggest sources of imbalance tends to be baseband filters and the modulator. The biggest source of gain inaccuracy tends to be the power amplifier.

BACKGROUND OF THE INVENTION

Wireless LAN standards require extremely good modulation accuracy and accuracy of transmitted power. Amplitude and phase imbalances between the in-phase and quadrature branches of the transmitter produce errors in the modulated signal. Good balance is difficult to obtain due to component variations and due to the fact that the amplitude and phase of the phase splitting circuits is frequency dependent. In addition imbalances occur because of fluctuating temperatures.

SUMMARY OF THE INVENTION

According to an embodiment of the invention, four data symbols are used as raw data, together with at least four transmitted symbols to arrive at several imbalance parameters, which may be used to modify subsequent data symbols. The four transmitted symbols may be sampled, and serve as the basis for calculating the energy of the four transmitted symbols. A calculation of alpha, epsilon and gain imbalance parameters may be made based on the four data symbols and the energy of the four transmitted symbols. Alpha, epsilon and gain are stored. First quadrature compensating of a next data symbol is done based on the alpha, epsilon, and gain to produce a first quadrature compensated data symbol (FQCDS). Second quadrature compensating the next data symbol is done based on the alpha, epsilon and gain to produce a second quadrature compensated data symbol (SQCDS). First in-phase compensating of the next data symbol is done to produce a first in-phase compensated data symbol (FICDS). Second in-phase compensating of the next data symbol is done to produce a second in-phase compensated data symbol (SICDS).

According to another embodiment of the invention, alpha, epsilon and gain are available preset into appropriate storage. Each data symbol may be compensated based on this preset information. First quadrature compensating of a data symbol is done

based on the alpha, epsilon, and gain to produce a first quadrature compensated data symbol. Second quadrature compensating the data symbol is done based on the alpha, epsilon and gain to produce a second quadrature compensated data symbol. First in-phase compensating of the data symbol is done to produce a first in-phase compensated data symbol. Second in-phase compensating of the data symbol is done to produce a second in-phase compensated data symbol.

Among the benefits of the embodiments of the invention, the effects, at least of one time, of the phase and amplitude imbalance may be stored. In addition gain inaccuracies and local oscillator (LO) leakage may be measured and stored in a new form as a set of imbalance parameters.

The first embodiment may routinely sample a transmitter output to obtain timely imbalance parameters (referred to sometimes as α, ε and g) which may be influenced in part, by data sampled at a baseband level, prior to operation of a inverse fast fourrier transform (IFFT). The routine updating of imbalance parameters may reflect a changing environment, including variation of amplification on several frequencies and the effects of changing temperatures.

The embodiments, once having obtained imbalance parameters, may apply those imbalance parameters to predistort or compensate one or more baseband symbols so that the amplified signal output of the amplifier has a narrower range of errors in relation to phase, amplitude and gain.

BRIEF DESCRIPTION OF THE DRAWINGS

The disclosed inventions will be described with reference to the accompanying drawings, which show important sample embodiments of the invention, wherein:

Fig. 1 shows a prior art Orthogonal Frequency Division Multiplexing (OFDM) transmitter;

Fig. 2 shows a transmitter according to an embodiment of the invention; and

Fig. 3 shows a transmitter according to a factory-calibrated embodiment of the invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Fig. 1 shows an Orthogonal Frequency Division Multiplexing (OFDM) transmitter **101**, which is known in the art. Binary data enters the mapping block **103**, which converts the data into N pairs of I and Q signals, wherein N represents the number of subcarrier frequencies that are modulated by the signals These N pairs are fed into

Inverse Fast Fourier Transform (IFFT) **106**. IFFT **106** produces the $S_I(t)$ (or in-phase) signal **107** and the $S_Q(t)$ (or quadrature) signal **109** according to the following formula:

$$S_I(t)=\sum_{n=1}^{N/2} a_{N/2-n}\cos(n\omega_c t-\varphi_{N/2-n})+a_{N/2+n+1}\cos(n\omega_c t+\varphi_{N/2+n+1}) \qquad [1]$$

$$S_Q(t)=\sum_{n=1}^{N/2} -a_{N/2-n}\sin(n\omega_c t-\varphi_{N/2-n})+a_{N/2+n+1}\sin(n\omega_c t+\varphi_{N/2+n+1}) \qquad [2]$$

where a, φ, ω and N are the amplitude, phase and the frequency of the carriers, and N is the number of subcarriers, respectively. Digital to analog converter (DAC) **111** converts $S_i(t)$ **107** to analog. Similarly DAC **113** converts $S_q(t)$ **109** to analog. The analog signals enter the modulator **150** and are subsequently amplified by amplifier **151**. The modulator may be a direct conversion-type of modulator.

Fig. 2 shows a transmitter according to an embodiment of the invention. Directional coupler **201** may obtain the waveform as amplified by amplifier, that is a transmitted symbol. Subsequently transmitted symbols are next symbols. The signal is provided to a squarer or power detector **203,** which may be an analog device. An analog to digital converter follows **205**. The signal may be integrated over the symbol duration using integrator **207**, to provide an energy value **209** or energy of the transmitted symbol according to the following equation:

$$P_k=\int_0^{T_s} s_{o,k}^2(t)\,dt, \qquad [3]$$

The term k represents the symbol number and T_S is the duration of one symbol. The energy **209** of four transmitted symbols thus is P_1, P_2, P_3, and P_4.

Amplitude $a_{k,n}$ and phase $\Phi_{k,n}$ of subcarrier number n may be calculated as follows by S-calc **245**:

$$a_{k,n}=\sqrt{d_{I,k,n}^2+d_{Q,k,n}^2}$$
$$\phi_{k,n}=\arctan\left(\frac{d_{Q,k,n}}{d_{I,k,n}}\right) \qquad [4]$$

where ak,n and phase Φk,n are the amplitude of subcarrier n and symbol k, respectively. Di,k,n and d Q,k,n are the subcarrier in-phase and quadrature signals respectively for subcarrier n and symbol k.

S-calc **245** may calculate S parameters for the four symbols over the set of subcarriers as follows:

$$S_{1,k} = \sum_{n=1}^{N}\left(d_{I,k,n}^2 + d_{Q,k,n}^2\right) - 2\sum_{n=1}^{N/2}\left(d_{I,k,N+1-n}d_{I,k,n} - d_{Q,k,N+1-n}d_{Q,k,n}\right) \qquad [5]$$

$$S_{2,k} = \sum_{n=1}^{N/2}\left(d_{I,k,N+1-n}d_{Q,k,n} + d_{Q,k,N+1-n}d_{I,k,n}\right) \qquad [6]$$

$$S_{3,k} = \sum_{n=1}^{N}\left(d_{I,k,n}^2 + d_{Q,k,n}^2\right) + 2\sum_{n=1}^{N/2}\left(d_{I,k,N+1-n}d_{I,k,n} - d_{Q,k,N+1-n}d_{Q,k,n}\right) \qquad [7]$$

where in-phase data $d_{I,1}..d_{I,N}$ and quadrature data $d_{Q,1}..d_{Q,N}$ **253** are available from mapper **241**.

One or several sets of four data symbols may be used during the sampling period when imbalance parameters, gain and LO signal leakage are determined.

The S parameters form the basis for F parameters and H parameters as shown below:

$$F_1 = S_{1,2}\left(S_{2,3}S_{3,4} - S_{2,4}S_{3,3}\right) + S_{1,3}\left(S_{2,4}S_{3,2} - S_{2,2}S_{3,4}\right) + S_{1,4}\left(S_{2,2}S_{3,3} - S_{2,3}S_{3,2}\right)$$

$$F_2 = S_{1,1}\left(S_{2,4}S_{3,3} - S_{2,3}S_{3,4}\right) + S_{1,3}\left(S_{2,1}S_{3,4} - S_{2,4}S_{3,1}\right) + S_{1,4}\left(S_{2,3}S_{3,1} - S_{2,1}S_{3,3}\right)$$

$$F_3 = S_{1,1}\left(S_{2,2}S_{3,4} - S_{2,4}S_{3,2}\right) + S_{1,2}\left(S_{2,4}S_{3,1} - S_{2,1}S_{3,4}\right) + S_{1,4}\left(S_{2,1}S_{3,2} - S_{2,2}S_{3,1}\right)$$

$$F_4 = S_{1,1}\left(S_{2,3}S_{3,3} - S_{2,2}S_{3,3}\right) + S_{1,2}\left(S_{2,1}S_{3,3} - S_{2,3}S_{3,1}\right) + S_{1,3}\left(S_{2,2}S_{3,1} - S_{2,1}S_{3,2}\right)$$

$$H_1 = S_{2,2}\left(S_{1,4} - S_{1,3}\right) + S_{2,3}\left(S_{1,2} - S_{1,4}\right) + S_{2,4}\left(S_{1,3} - S_{1,2}\right)$$

$$H_2 = S_{2,1}\left(S_{1,3} - S_{1,4}\right) + S_{2,3}\left(S_{1,1} - S_{1,4}\right) + S_{2,4}\left(S_{1,1} - S_{1,3}\right)$$

$$H_3 = S_{2,1}\left(S_{1,4} - S_{1,2}\right) + S_{2,2}\left(S_{1,1} - S_{1,4}\right) + S_{2,4}\left(S_{1,2} - S_{1,1}\right)$$

$$H_4 = S_{2,1}\left(S_{1,2} - S_{1,3}\right) + S_{2,2}\left(S_{1,3} - S_{1,1}\right) + S_{2,3}\left(S_{1,1} - S_{1,2}\right). \qquad [8]$$

The energy **209** of the four transmitted symbols may contribute to the calculation of the P_{LO} local oscillator signal power as follows:

$$P_{LO} = -\frac{P_1F_1 + P_2F_2 + P_3F_3 + P_4F_4}{P_1H_1 + P_2H_2 + P_3H_3 + P_4H_4}, \qquad [9]$$

The S parameters from S-calc **245** and the P parameters from **209** may be used to compute the epsilon, alpha and g and store the values as imbalance parameters to a cache or storage **250**:

$$\varepsilon = \sqrt{\frac{P_1\left(S_{2,3}\left(P_{LO}+S_{3,2}\right)-S_{2,2}\left(P_{LO}+S_{3,3}\right)\right)+P_2\left(S_{2,1}\left(P_{LO}+S_{3,3}\right)-S_{2,3}\left(P_{LO}+S_{3,1}\right)\right)+P_3\left(S_{2,2}\left(P_{LO}+S_{3,1}\right)-S_{2,1}\left(P_{LO}+S_{3,2}\right)\right)}{P_1\left(S_{1,3}S_{2,2}-S_{1,2}S_{2,3}\right)+P_2\left(S_{1,1}S_{2,3}-S_{1,3}S_{2,1}\right)+P_3\left(S_{1,2}S_{2,1}-S_{1,1}S_{2,2}\right)}}$$

$$\alpha = \arcsin\left(\frac{-1}{4\varepsilon}\frac{P_1\left(S_{1,2}\left(P_{LO}+S_{3,3}\right)-S_{1,3}\left(P_{LO}+S_{3,2}\right)\right)+P_2\left(-S_{1,1}\left(P_{LO}+S_{3,3}\right)+S_{1,3}\left(P_{LO}+S_{3,1}\right)\right)+P_3\left(S_{1,1}\left(P_{LO}+S_{3,2}\right)+S_{1,2}\left(-S_{3,1}-P_{LO}\right)\right)}{P_1\left(S_{1,2}S_{2,3}-S_{1,3}S_{2,2}\right)+P_2\left(S_{1,3}S_{2,1}-S_{1,1}S_{2,3}\right)+P_3\left(S_{1,1}S_{2,2}-S_{1,2}S_{2,1}\right)}\right)$$

[11]

$$g_t = \frac{4P_1}{\varepsilon S_{1,1} + 4\varepsilon\sin(\alpha)S_{2,1} + S_{3,1} + P_{LO}} \qquad [12]$$

The epsilon, alpha and g values may then be stored unchanged in **250.** Alternatively, the epsilon, alpha and g values may be updated whenever an additional data symbol in the form of in-phase data and quadrature data **253** is available, or less frequently.

Yet another arrangement for determining epsilon, alpha and g values includes calculating a first alpha, first epsilon and a first gain based on the energy of the at least four transmitted symbols; and calculating a second alpha, second epsilon and a second gain based on the energy of the next data symbol. The final steps to reach the alpha, epsilon and gain values may include calculating a alpha based on a average of the first alpha and the second alpha; calculating a epsilon based on a average of the first epsilon and the second epsilon; and calculating a gain based on a average of the first gain and the second gain. Thus during a compensation period, the imbalance parameters in use may be averaged values. Many forms of averaging may be used, including weighting a more recent value more heavily, e.g. weighting a second alpha heavier than a first alpha.

The duration when the compensator provides the compensated data signals is known as the compensation period. The compensator **251** may operate in a sampling period acquisition mode where no changes are made to data symbols provided to the compensator, and such symbols are placed onto the IFFT-bus **261** unchanged by the compensator. The compensator may operate in a feedback mode during a compensation period where the compensator **251** provides the compensated in-phase baseband, i.e. first in-phase compensated data symbol (FICDS) **263**, and a second in-

phase compensated data symbol (SICDS) **265**, and compensated quadrature baseband, i.e. a first quadrature compensated data symbol (FQCDS) **262**, second quadrature compensated data symbol (SQCDS) **264**, signals to the IFFT **271**.

Fig. 3 shows an embodiment that dispenses with the use of a persistent feedback loop in favor of testing the transmitter output, data symbols at the time of manufacture, and storing the resultant imbalance parameters, epsilon, alpha and gain, in a storage **350** which may be non-volatile. The factory calibration apparatus may sample symbols, denoted by $d_{I,1}..d_{I,N}$ and $d_{Q,1}..d_{Q,N}$ **353** as well as sample and amplifier output **301** to derive, by methods similar to those used in Fig. 2, to obtain the epsilon, alpha and gain applicable to symbols transmitted by the amplifier. The data symbols **353** may each comprise a first quadrature subcarrier **354**, a first in-phase subcarrier **355**, a second quadrature subcarrier **356** and a second in-phase subcarrier **357**. Thus, a feedback loop may not be required in the final product that is shipped.

The hardware for the factory-calibrated embodiment may include a compensator **351** reading from the storage **350**. Such an apparatus may be inserted to intercept the signals of the prior-art mapper **341**, changing the in-phase baseband and quadrature baseband **353** signals to compensated data symbols **361**. IFFT **371** produces the I signal **307** and the Q signal **309** by means known in the art. Modulator **381** may operate as an OFDM and may be followed by amplifier **391**.

Once the alpha, epsilon and gain values are known, by the feedback loop in fig.2, compensation of the current data symbol presented to the compensator **251** may be performed in an operation known as compensating. Each subcarrier component of the current data symbol may be referred to as a next symbol in relation to a data symbol that provided data for computing the alpha, epsilon and gain values of the storage **250**. Compensator **251** may perform at least four operations. Compensator **251** may perform at least one first quadrature compensating of a next data symbol, thus obtaining the FQCDS, or $d'_{Q,n}$:

$$d'_{Q,n} = \frac{g_w}{g}\frac{d_{Q,n}(1+\varepsilon\cos(\alpha)) + d_{Q,(n+N/2)}(1-\varepsilon\cos(\alpha)) + \varepsilon\sin(\alpha)(d_{I,n} - d_{I,(n+N/2)})}{2\varepsilon\cos(\alpha)}, \quad [13]$$

for each n valued at 1 through N/2. Compensator **251** may perform at least one second quadrature compensating of a next data symbol, thus obtaining the SQCDS or $d'_{Q,n}$:

$$d'_{Q,n} = \frac{g_w}{g}\frac{d_{Q,(n-N/2)}(1-\varepsilon\cos(\alpha)) + d_{Q,n}(1+\varepsilon\cos(\alpha)) + \varepsilon\sin(\alpha)(d_{I,n} - d_{I,(n-N/2)})}{2\varepsilon\cos(\alpha)}, [14]$$

for each n valued at N/2+1 through N. Compensator **251** may perform at least one first in-phase compensating of a next data symbol, thus obtaining the FICDS, or $d'_{I,n}$:

$$d'_{I,n} = \frac{g_w}{g}\frac{d_{I,n}(1+\varepsilon\cos(\alpha)) + d_{I,(n+N/2)}(\varepsilon\cos(\alpha)-1) - \varepsilon\sin(\alpha)(d_{Q,n}+d_{Q,(n+N/2)})}{2\varepsilon\cos(\alpha)}, \quad [15]$$

for each n valued at 1 through N/2. Compensator **251** may perform at least one second in-phase compensating of a next data symbol, thus obtaining the SICDS, or $d'_{I,n}$:

$$d'_{I,n} = \frac{g_w}{g}\frac{d_{I,(n-N/2)}(\varepsilon\cos(\alpha)-1) + d_{I,n}(1+\varepsilon\cos(\alpha)) - \varepsilon\sin(\alpha)(d_{Q,n}+d_{Q,(n-N/2)})}{2\varepsilon\cos(\alpha)}, \quad [16]$$

for each n valued at N/2+1 through N.

In each of the foregoing four equations, g_w is the wanted gain, which may be set to a value desired by the operator of the transmitter. If it is desired to use an averaged value of α, ε and g, those values may be used if previously stored in cache **250**.

Although the invention has been described in the context of particular embodiments, various alternative embodiments are possible. For example, other transmitters that have baseband I and Q signals of the form shown in equations [1] and [2] may benefit from compensation as shown herein. In addition, calculation of imbalance parameters may occur following the transmission of most symbols, or less frequently, e.g. near the beginning of a packet. Thus, while the invention has been particularly shown and described with respect to specific embodiments thereof, it will be understood by those skilled in the art that changes in form and configuration may be made therein without departing from the scope and spirit of the invention.